Advances in 3D Realistic Modeling of Solar-type Stars to Study Stellar Jitter and Photospheric and Subsurface Dynamics

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Target Stars

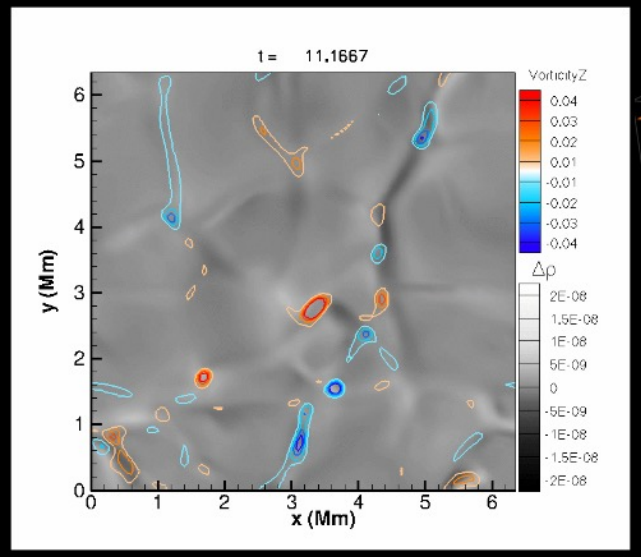
Star	Mass	Teff	log(g)	[Fe/H]*
HD209458	1.05	6095	4.314	-0.144
HD121504	1.18	6067	4.355	0.236
HD25171	1.08	6169	4.329	-0.032
HD49674	1.00	5597	4.408	0.126
HD69830	0.87	5383	4.469	0.038
Sun	1.00	5777	4.438	0.0
Stars	1.4 – 2	6501–8630	4.135–4.209	-0.3–0.2

StellarBox code (Wray et al., 2015; 2018)

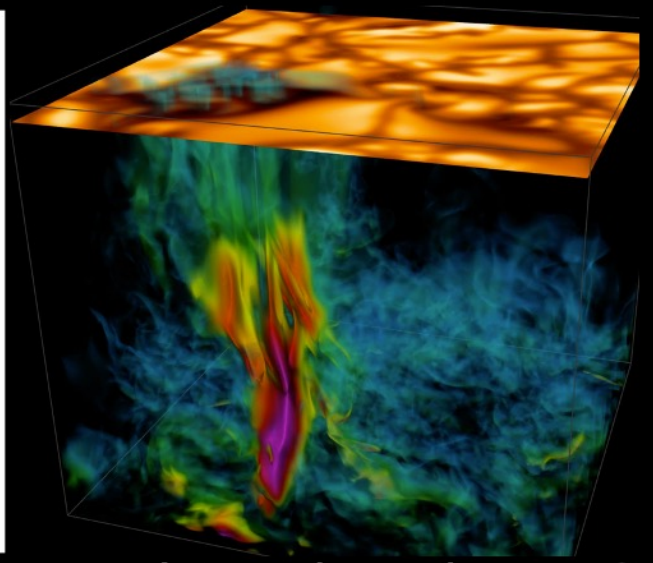
- Compressible plasma flows in a highly stratified medium
- 3D multi-group radiative energy transfer between the fluid elements
- **Real-gas equation of state**
- Ionization and excitation of all abundant species
- Small-scale turbulence
  - LES: Smagorinsky model (including its dynamic form)
  - DNS + Hyperviscosity approach
  - MHD subgrid models
- Magnetic effects
- Rotation
- **Internal structure**
- **Opacity tables**

3D realistic modeling of the stellar dynamics

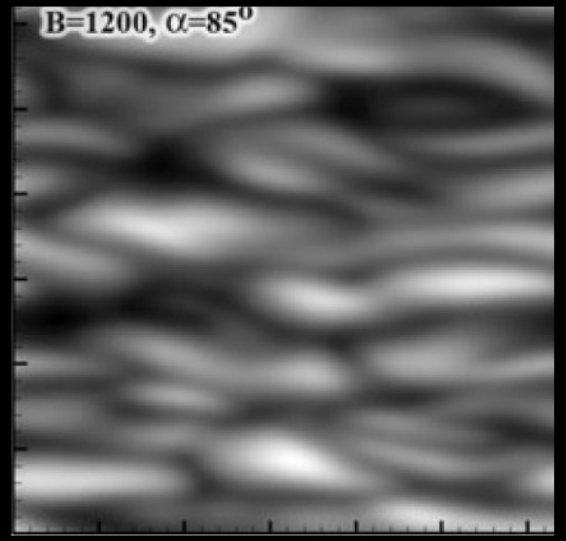
Acoustic waves excitation



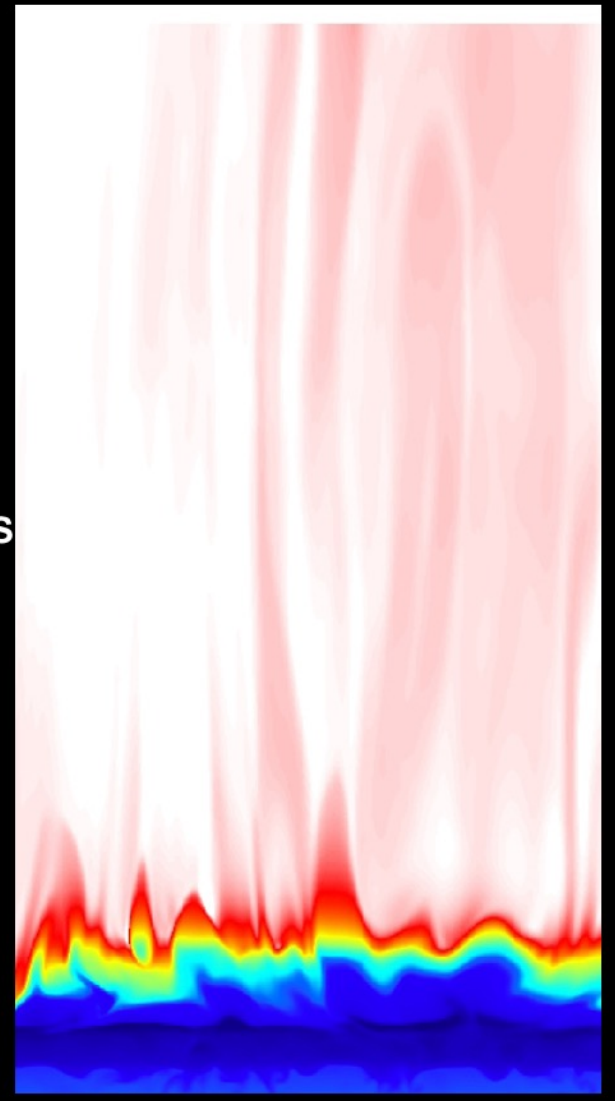
Magnetic structures formation



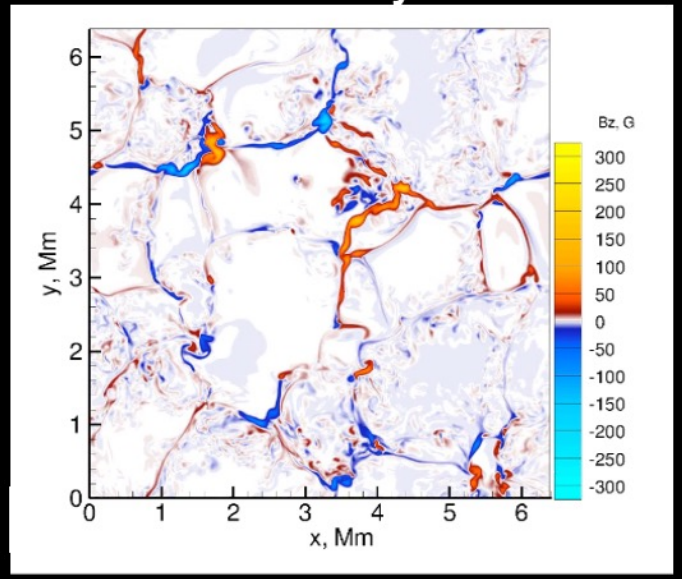
Self organization processes in magnetic field



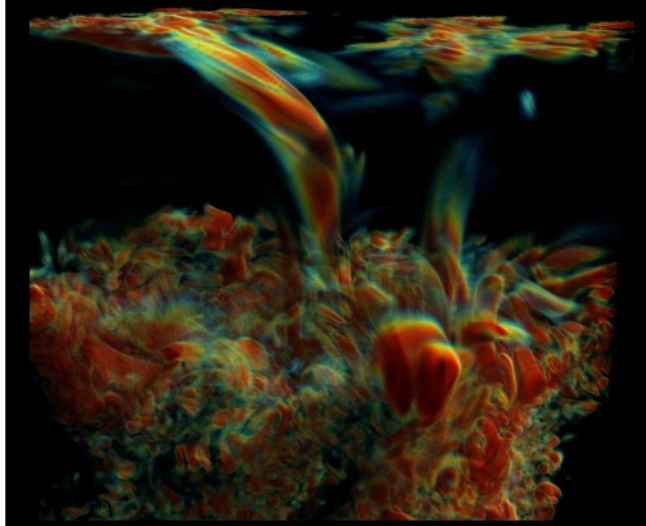
Corona structure and dynamics



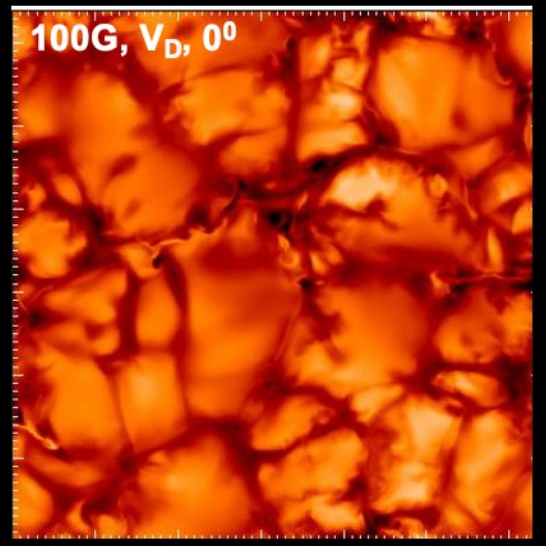
Small-scale dynamo



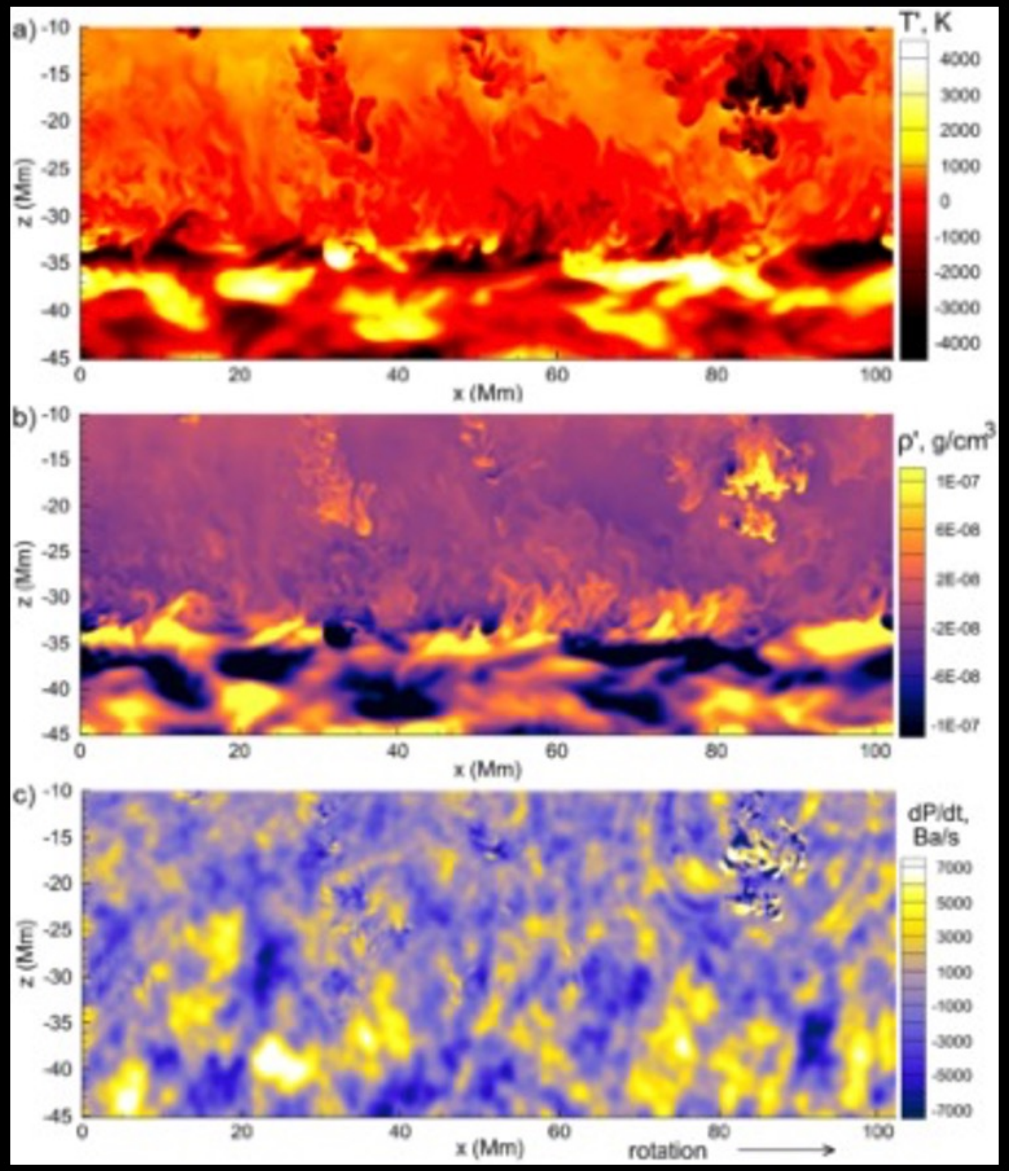
Jets and eruptions

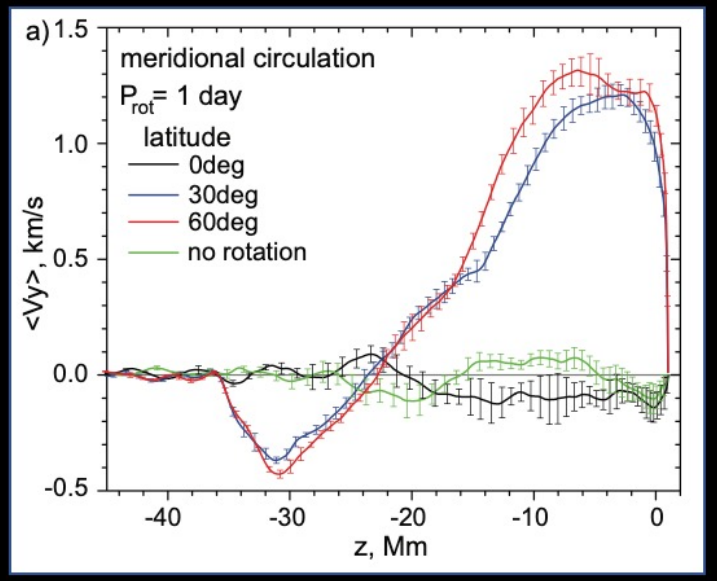


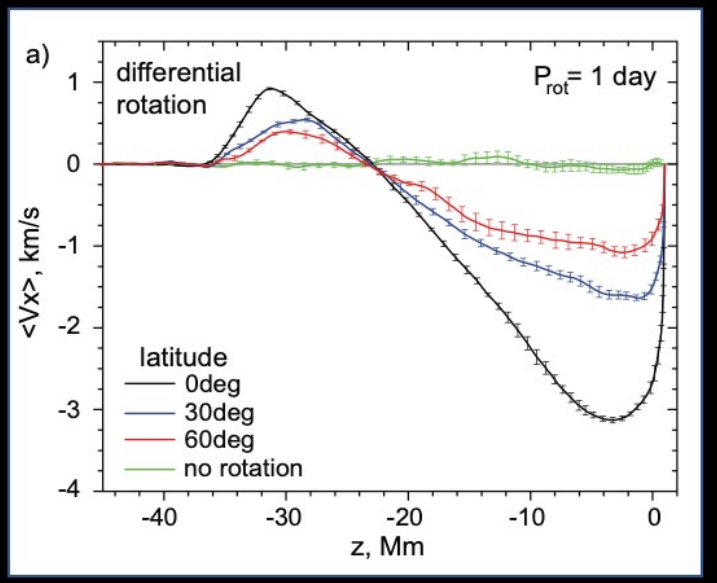
Spectral lines and observables

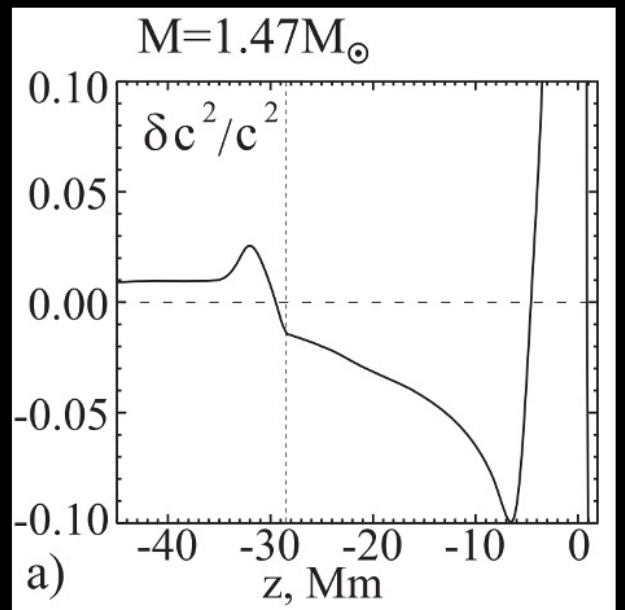


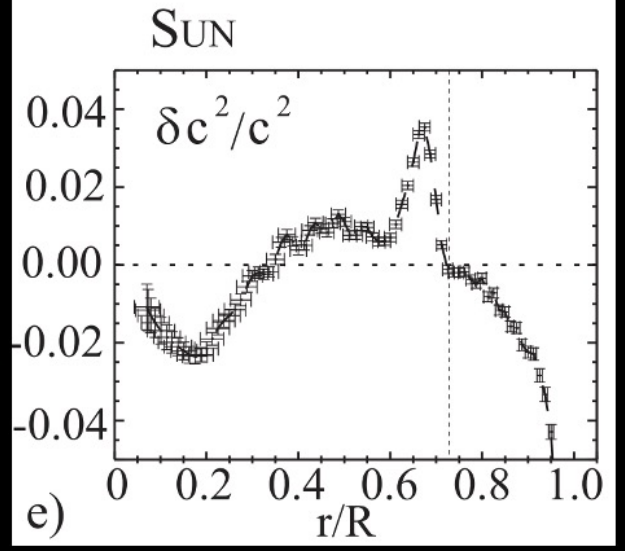
Internal dynamics of stars with shallow convection zone



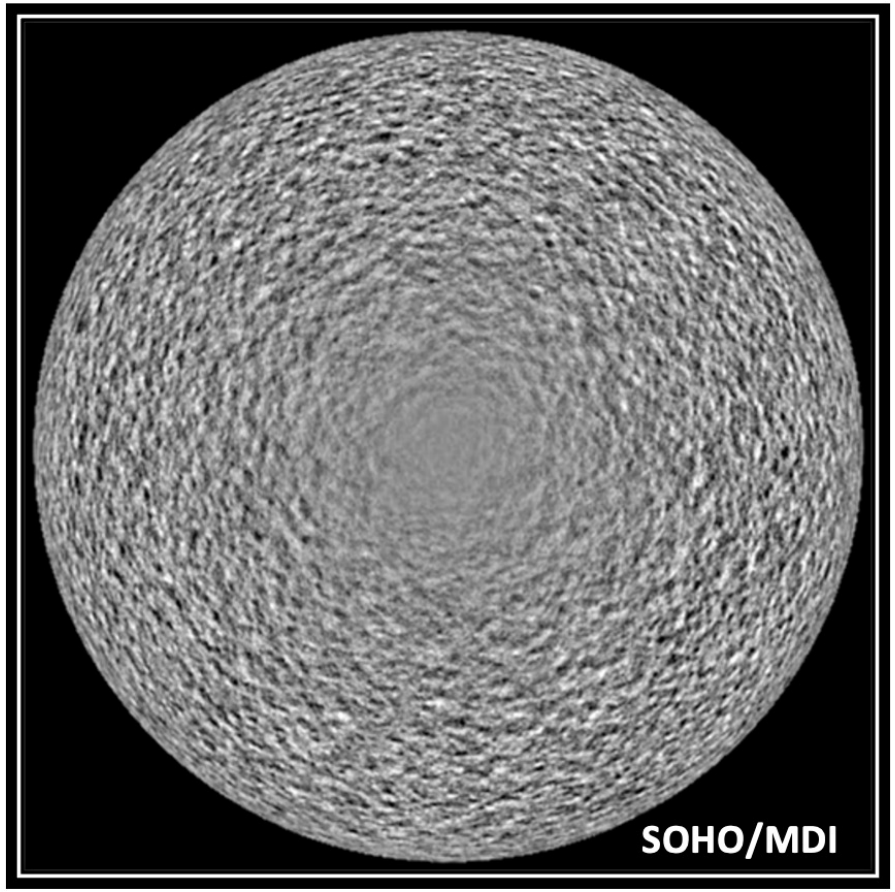




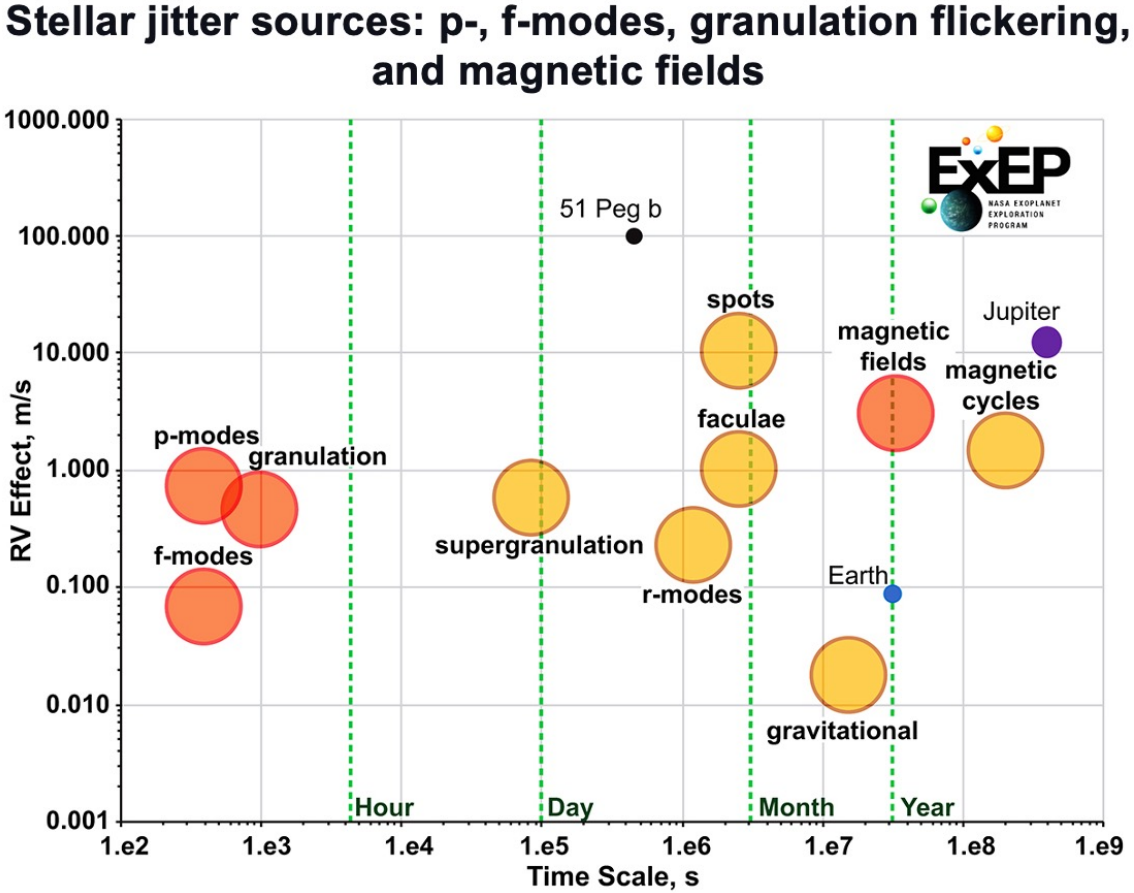




Contamination of the Radial Velocity Signal with Stellar Jitter

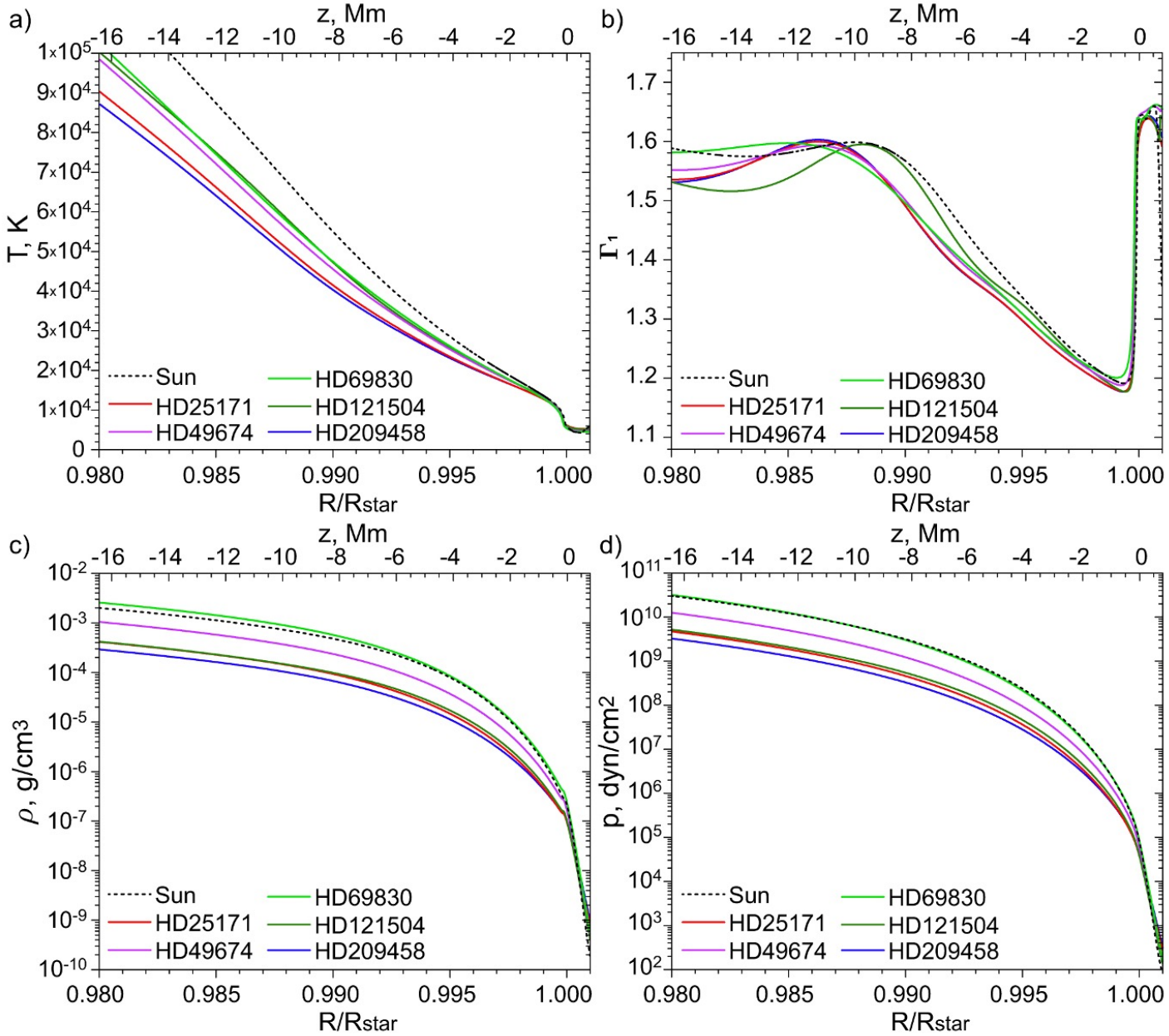


SOHO/MDI Dopplergram averaged over 30-min



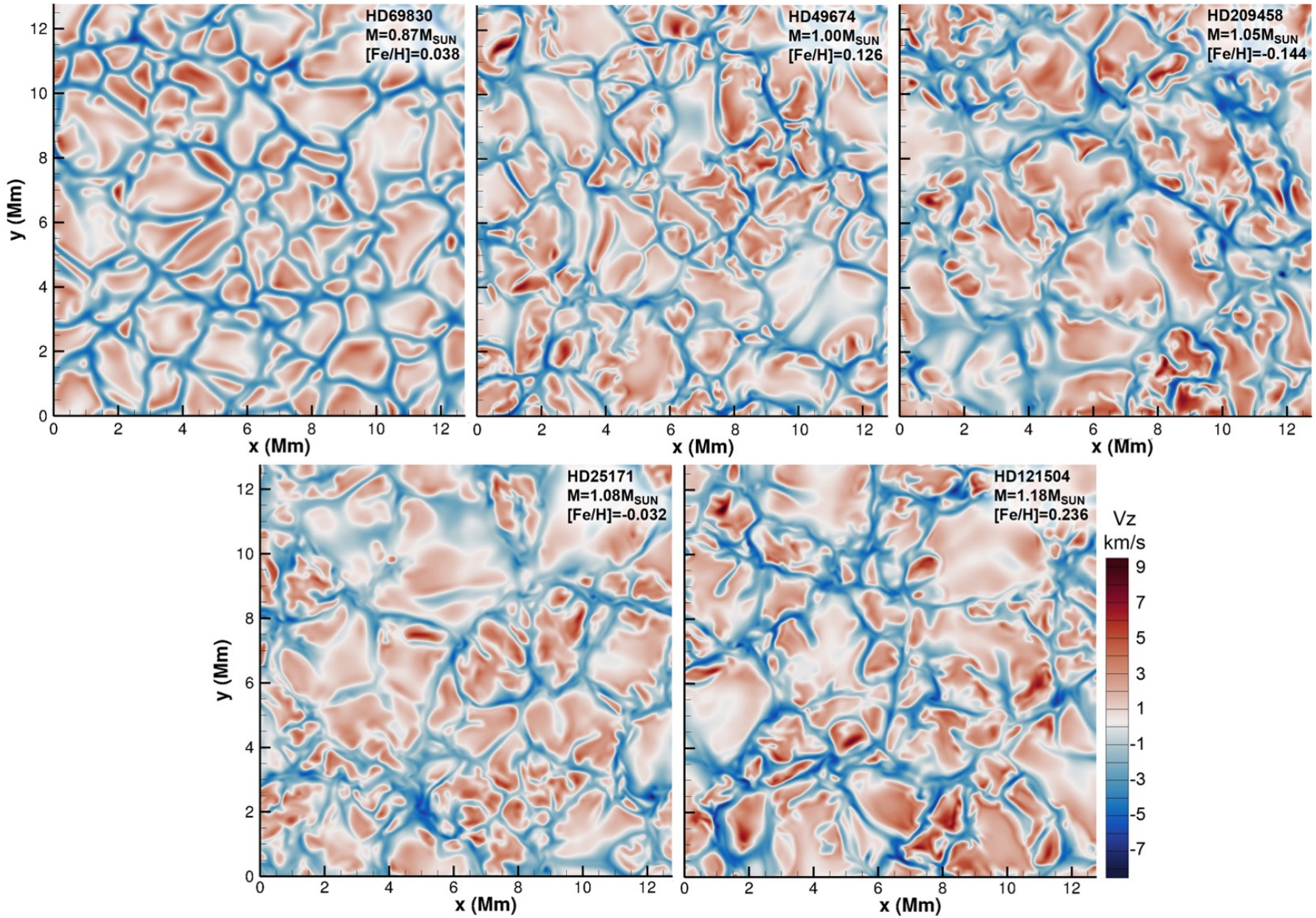
Schematic representation of correlated noise sources in the RV measurements originating from stellar surface convection and magnetic activity (modified from NASA EPRV working group report).

Initial conditions

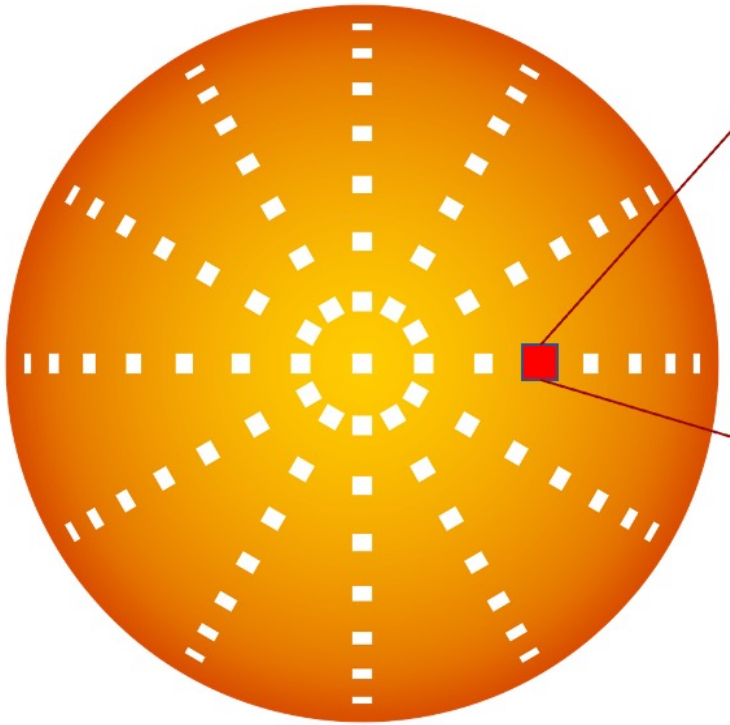


The models are obtained with the MESA code (Paxton et al. 2011)

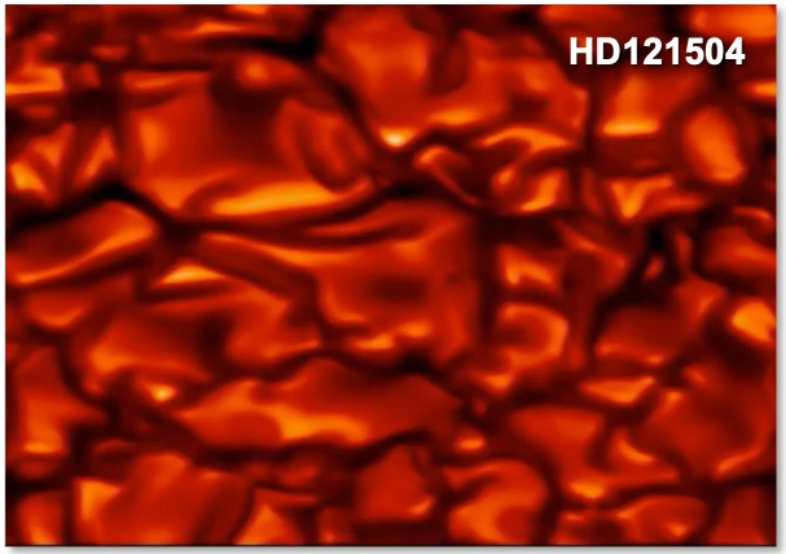
Granulation structure of the solar-type stars



Modeling of Stellar Jitter

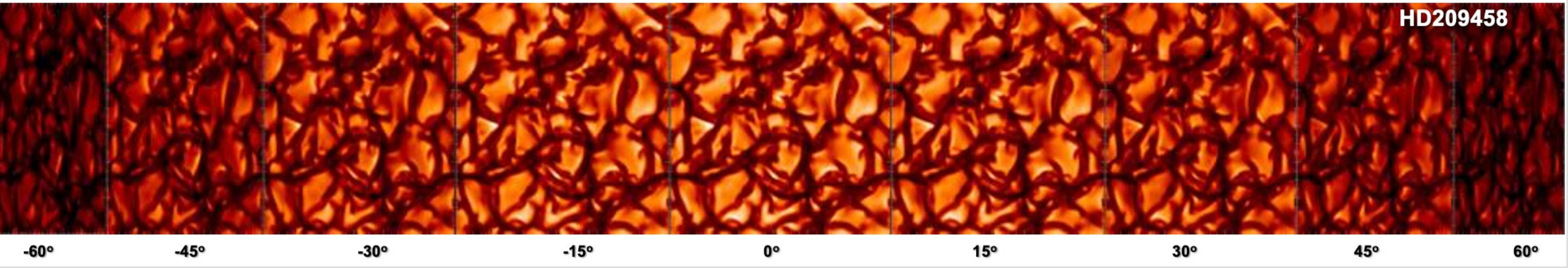


- 3D time-series of ultra-high spectral resolution data
- Line profile
- Doppler shift
- Line depth
- Bisector

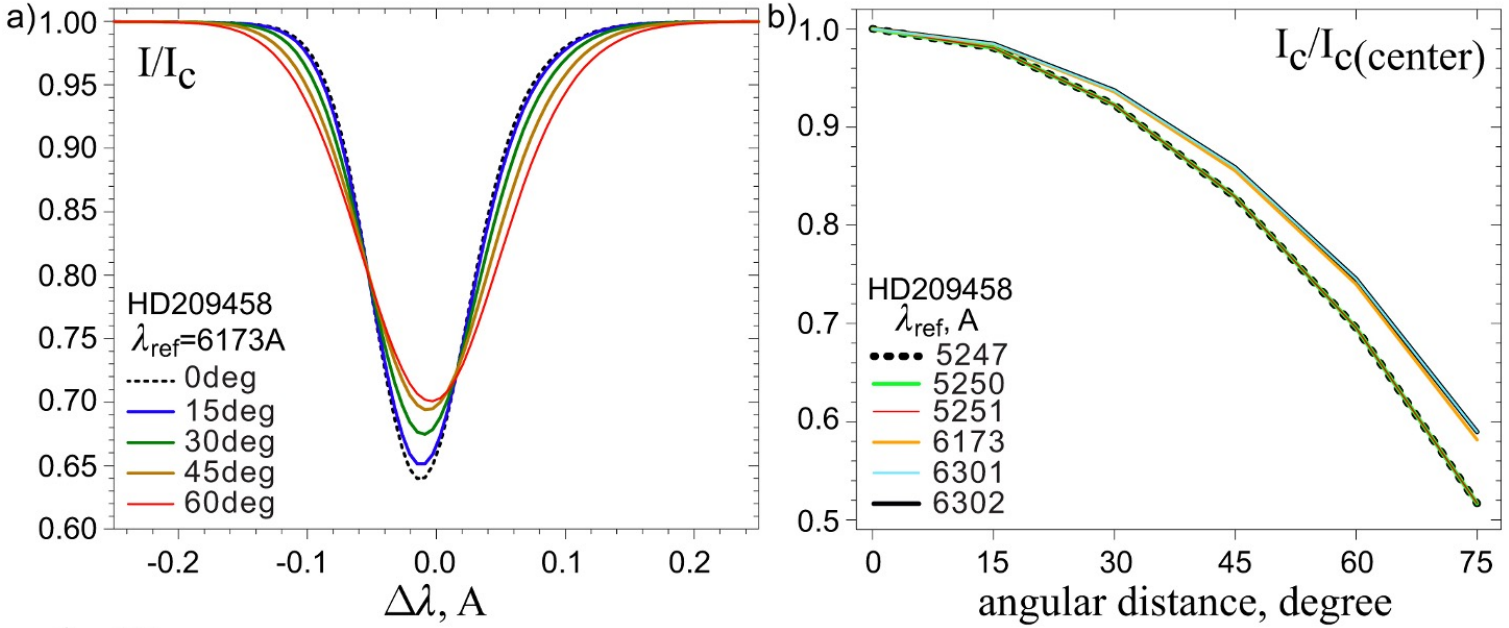


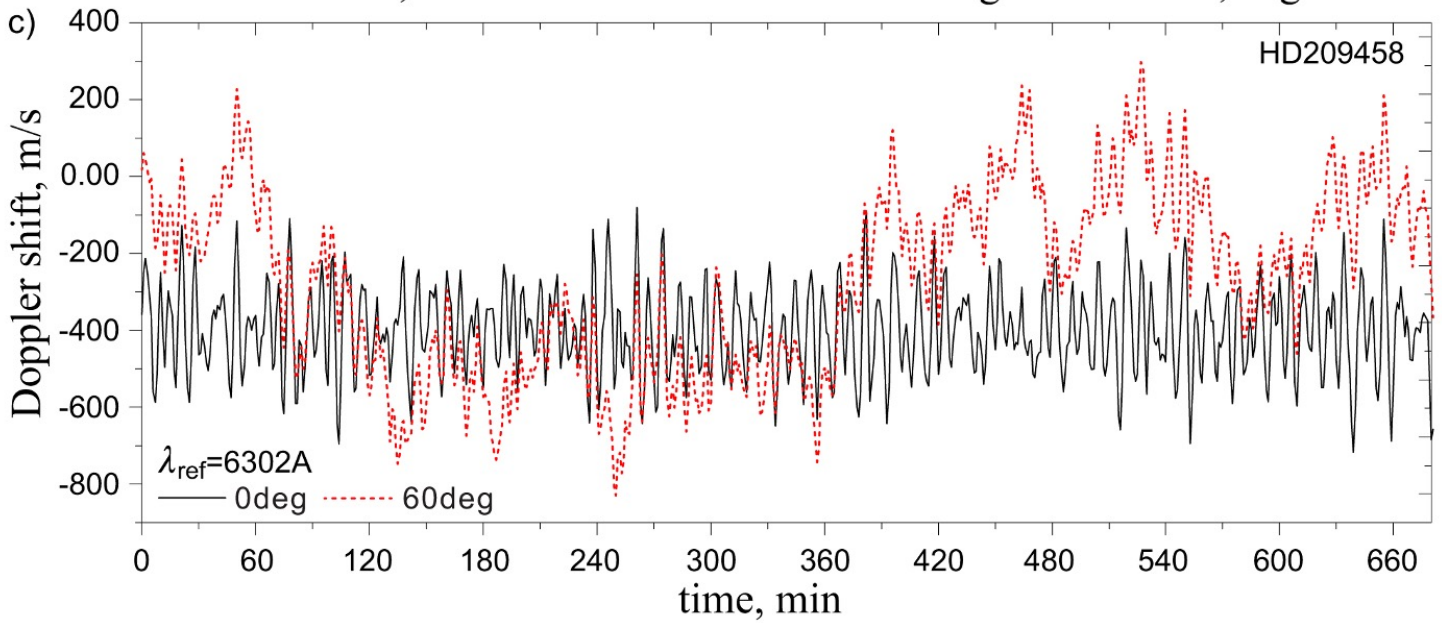
Synthetic image (Fe I, 6173A) of HD121504 planet-host star shows granulation dynamics of the photosphere at 45 degrees from the disk center.

Dravins et al., 2017; 2018; 2021
Cegla et al., 2012; 2013; 2018; 2019



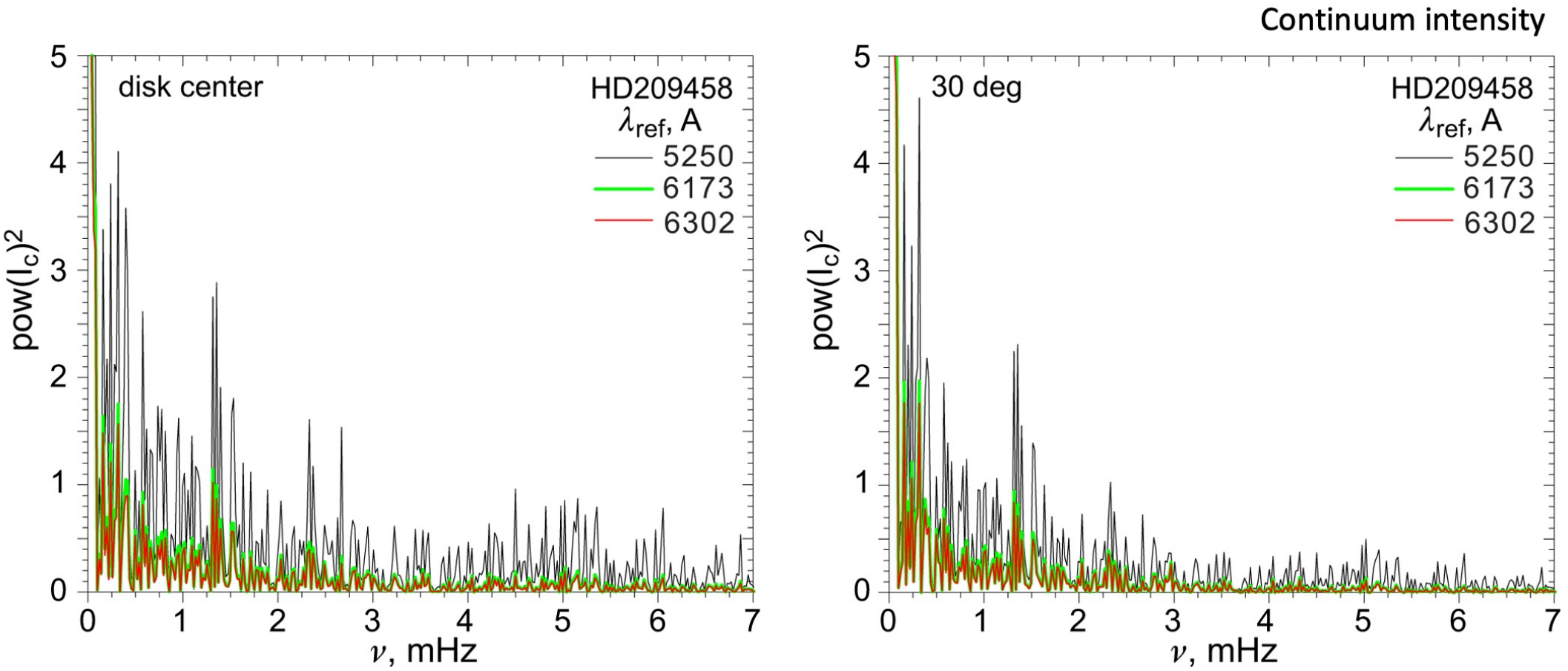
Planet-hosting star HD209458: center-to-limb effects





Center-to-limb effects:
a) changes in the spectral line (λref=6173A) at different distances from the disk center;
b) limb darkening profiles for six FeI lines;
c) Doppler shift variations as a function of time at the stellar disk center (black solid curve) and at 60 degrees from the disk center (red dotted curve).

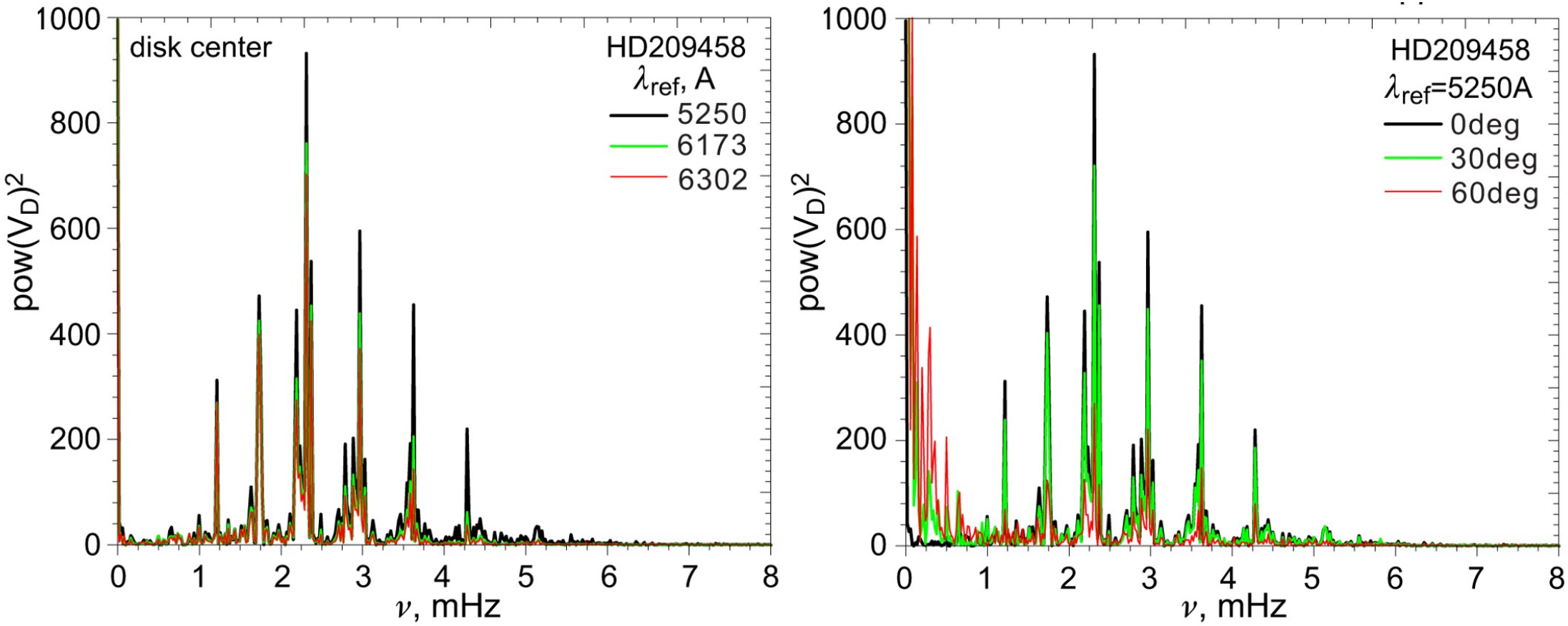
Planet-hosting star HD209458: oscillations



The power spectral density obtained from synthetic spectra of HD209458. The power spectral density of continuum intensity is shown for the disc center (left) and 30 degrees longitude (right).

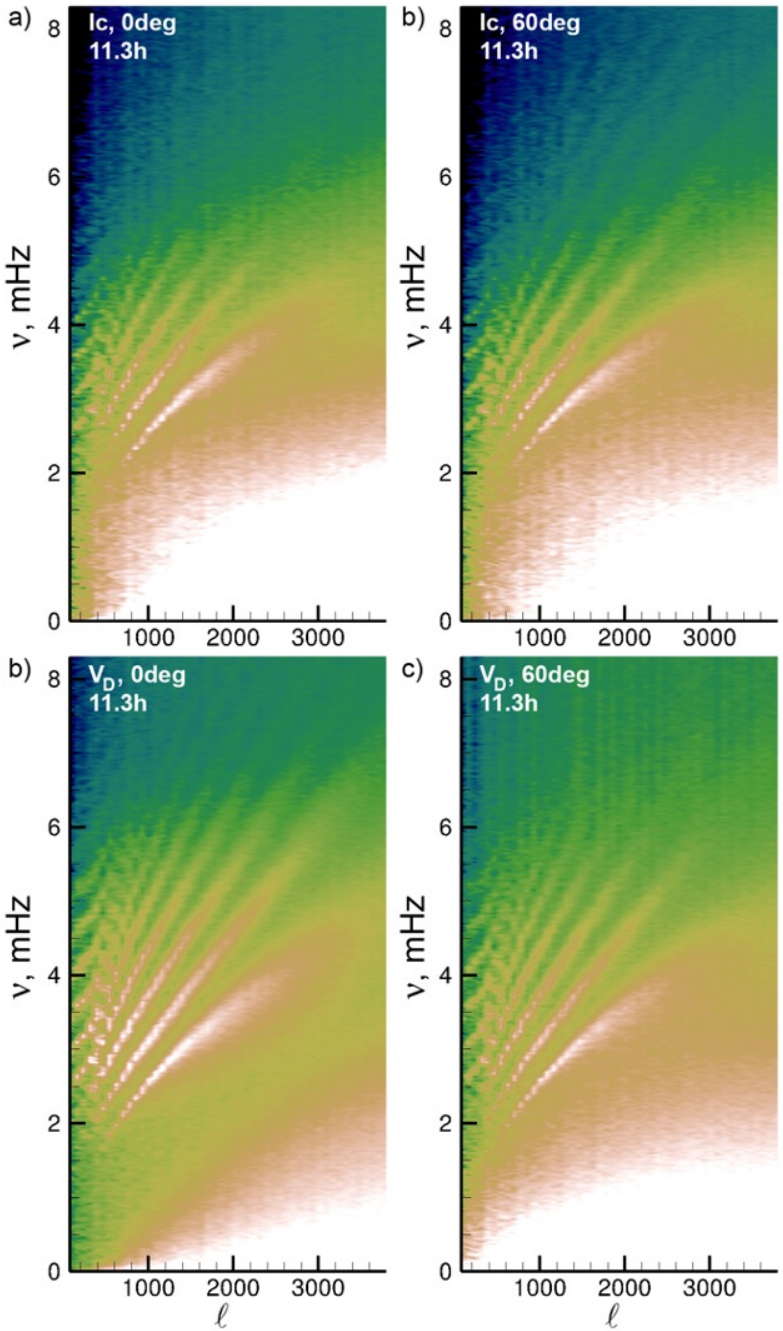
Planet-hosting star HD209458: oscillations

Doppler shift

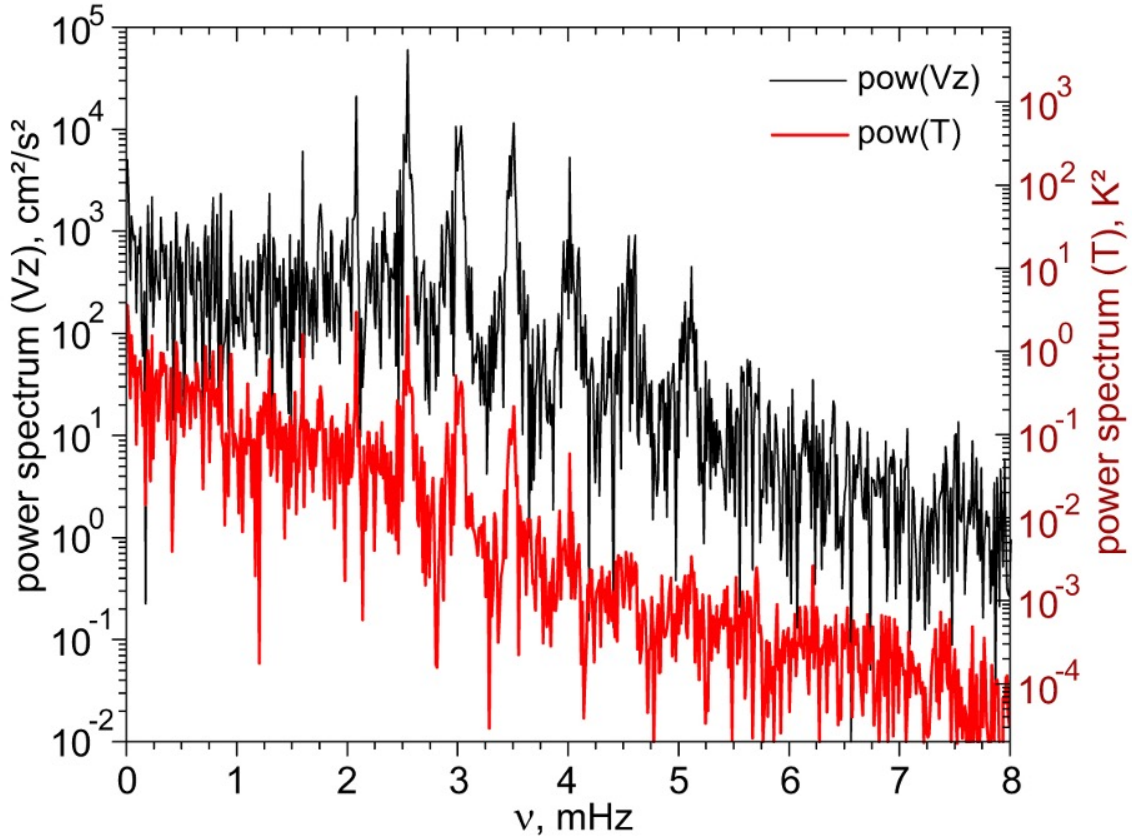


The power spectral density of the Doppler-shift corresponds to the simulated continuum intensity at the disk center computed from three spectral lines (left), and for three distances from the disk center (0, 30, and 60 degrees) for the single line 5250A (right).

Stellar jitter of solar convection



Ridges in the frequency-spherical harmonic degree (ν, l)-plane calculated from synthetic data (Fe I, 6173A): Doppler shift (bottom panels) and continuum intensity (upper panels) for 0 and 60 degrees from the solar disk center.



Power spectrum of the horizontally averaged radial velocities (black curve) and temperature (red curve) at the solar photosphere computed for 24 hours time series.

Conclusions

We presented initial results of modeling solar-type stellar dynamics to investigate the nature of stellar jitter and to develop data-characterization and filtering techniques for robust detection of Earth-mass exoplanets. We performed 3D radiative hydrodynamic simulations of stellar convection and computed synthetic spectroscopic observables of target stars. The initial results reproduce variations of spectral lines caused by convective motions and oscillations and allow us to investigate physical stellar properties such as oscillation power spectra, center-to-limb variations of spectral line profiles, and convective blue shift.

Our current effort is to produce longer time series of high-resolution hydrodynamic and MHD models and investigate techniques for filtering photospheric disturbances in spectroscopic observations.

❖ The work is supported by the NASA Extreme Precision Radial Velocity Foundation Science and Astrophysics Theory Programs.